

A photograph of an ancient mud-brick fortress or citadel built on a hill. The structure has a rectangular base with a smaller, square tower on top. The surrounding landscape is arid and rocky, with some low-lying vegetation. The sky is clear and blue.

Modeling Ancient Settlement Systems with the ENKIMDU Simulation Framework

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Argonne National Laboratory**

Modeling Ancient Settlement Systems

Goals

Examine the dynamics of **development and sustainability or demise of settlement systems** in both the rain-fed northern and irrigated southern regions of ancient Mesopotamia.

Mesopotamia as testbed for study of long-term human-environment interactions.

Approach

Apply complex adaptive systems, agent-based modeling techniques in a new, holistic simulation framework, to model **fine-scale interactions** among diverse natural processes and social processes on a daily basis across multi-generational timespans.

Participants

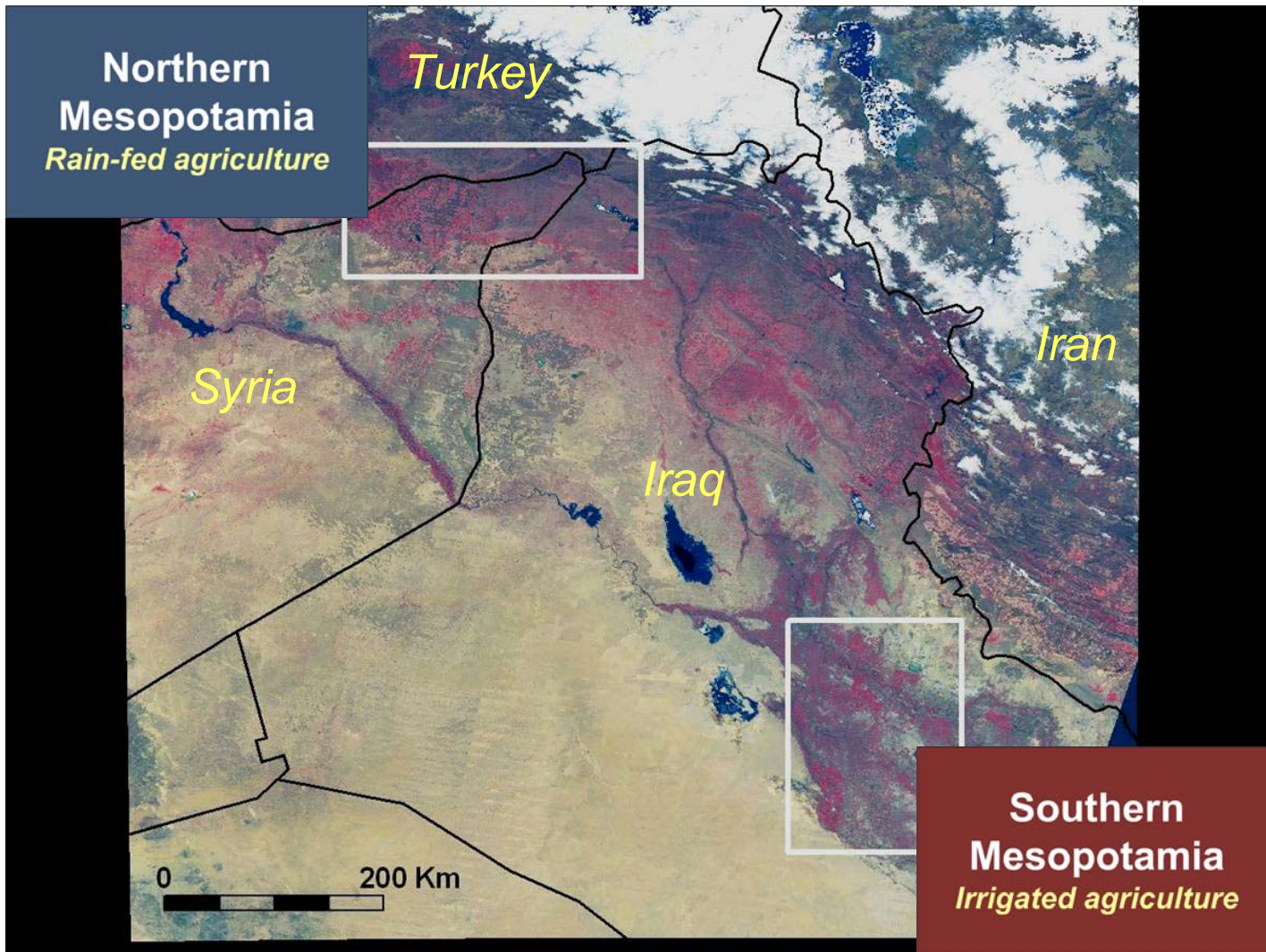
- The Oriental Institute of the University of Chicago
- Argonne National Laboratory
- The University of Edinburgh (UK)

Support



Five-year National Science Foundation
Biocomplexity in the Environment research grant

Mesopotamian Study Regions



Our Collaborative Development Process

Oriental Institute of the University of Chicago

Subject domain data
and conceptual models
derived from:



**EXTENSIVE
SITE
SURVEYS**

**CENTURIES
OF TEXTUAL
RECORDS**



**ETHNOGRAPHY
AND CULTURAL
ANALOGS**

"ENKIMDU"

HOLISTIC
AGENT-BASED
SIMULATION
FRAMEWORK

*... named in honor
of the ancient
Sumerian god of
agriculture and
irrigation*

Argonne National Laboratory Advanced Simulation Technologies Center

- Computer Modeling and Simulation Expertise
- Advanced Object-Based Discrete Event Simulation Frameworks:



A facility for
constructing
simulations for
complex,
heterogeneous
domains



A toolkit for
constructing
models of
complex social
behavior
patterns

Enabling Technologies: DIAS and FACET

DIAS and **FACET** together: a platform for building complex discrete event simulations with interacting social and natural system components. DIAS and FACET are:

- object-based, distributed, implemented in standard Java
- domain-neutral (not tied to a specific discipline or subject area)
- applications since 1996 include the following:



Integrated land management and land use planning at military training bases



Health care: agent-based physiological, clinical and logistical simulations



Avian social dynamics for an endangered species



Integrated oceanic and littoral systems simulation



Adaptive agent simulations for counter-drug operations analysis



Agricultural and social sustainability of ancient urban centers



Adaptive agent simulations for study of Joint Operating Concepts and Architectures



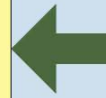
Agent-based agroeconomic analysis and planning tools for modern Thailand

The DIAS Modeling Paradigm

A DIAS problem domain representation consists of:

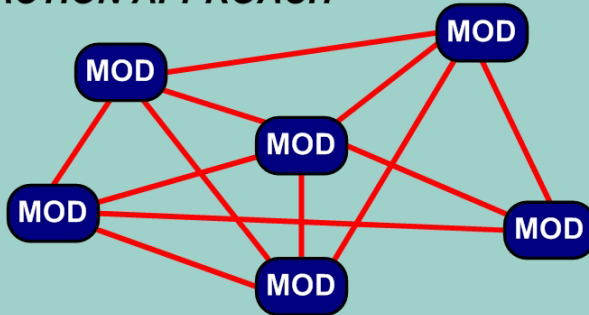
Software **objects** that represent the entities that comprise the domain

Simulation **models** that express the behaviors of the domain entities



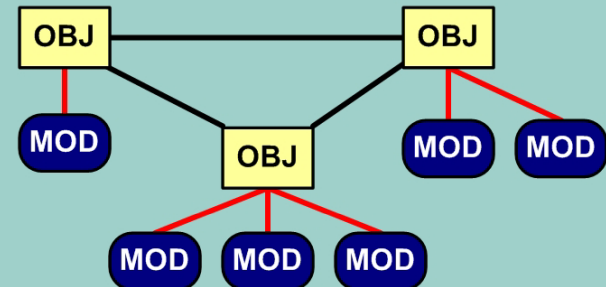
The models communicate only with domain objects, and not with each other – Thus easy to add models, swap models in and out without re-coding.

TRADITIONAL MODEL-TO-MODEL INTERACTION APPROACH



(Many inter-model links to be maintained - brittle and fragile)

DIAS OBJECT-MODEL INTERACTIONS



(Fewer, simpler links to be maintained - flexible and robust)

For added flexibility, models are *not* built directly into the objects they serve. Instead they are linked to objects on-the-fly at run time, based on simulation context

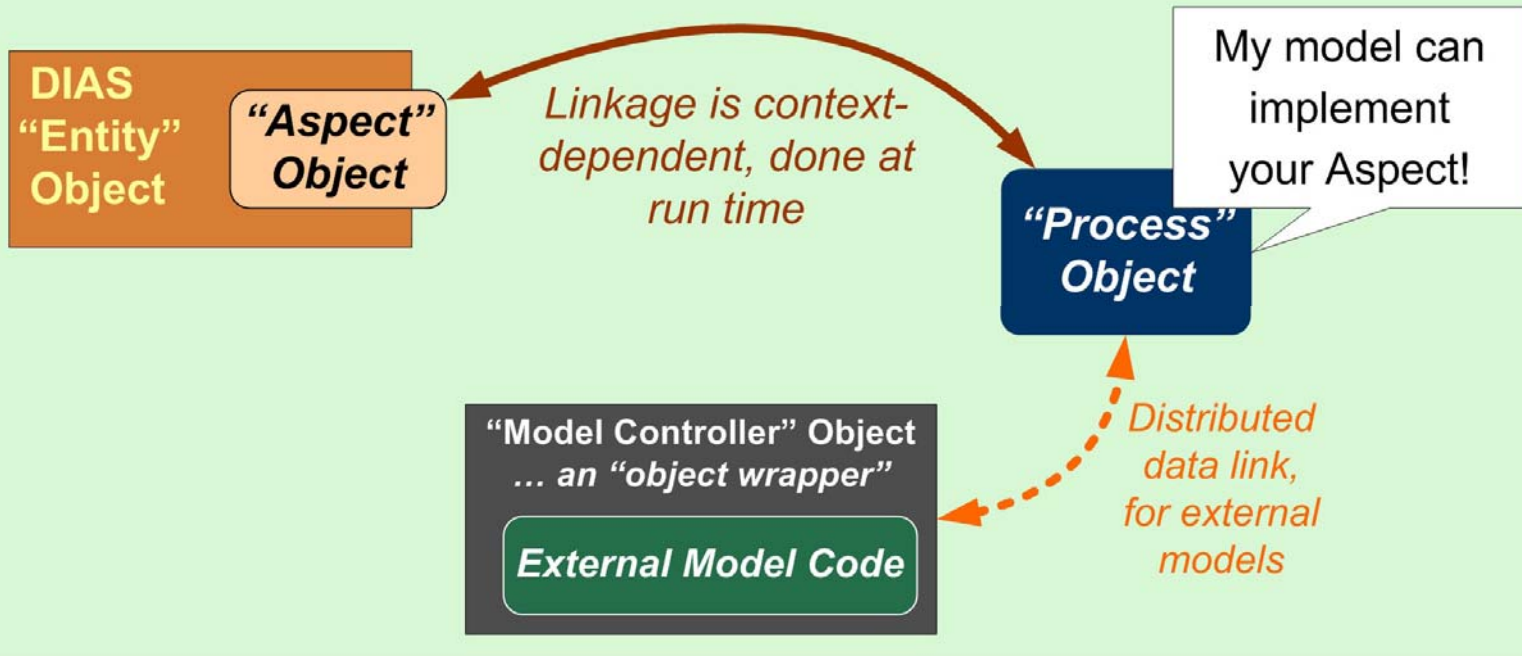
More on Key DIAS Design Features

Abstraction of domain object dynamic behaviors

DIAS domain objects declare behaviors *abstractly*, via **Aspect** Objects, which do *not* carry actual implementation of the behaviors.

Encapsulation and formal definition of model functionality

DIAS **Process** Objects represent and formally define specific models that can implement specific abstract domain object behaviors (Aspects).



FACET: Characteristics of Societal Processes

Societal processes often seem to operate on the **EDGE OF CHAOS** ... this is quite a challenge for modeling and simulation.

FACET explicitly addresses many of the distinctive characteristics of *societal* processes (in contrast to “natural,” or physics-based processes):

- Processes usually involve some level of **cooperation** among participating “agents” (e.g., Persons or Organizations).
- Agents may be **concurrently** involved in several behavior patterns and may need to **prioritize** their interactions and commitments to be able to participate in these patterns.
- Behavior patterns may **branch** to follow several alternative paths and may segue into other patterns, based on social context.
- Processes can be **interrupted** or preempted – to be resumed later, or abandoned for more context-appropriate activities.

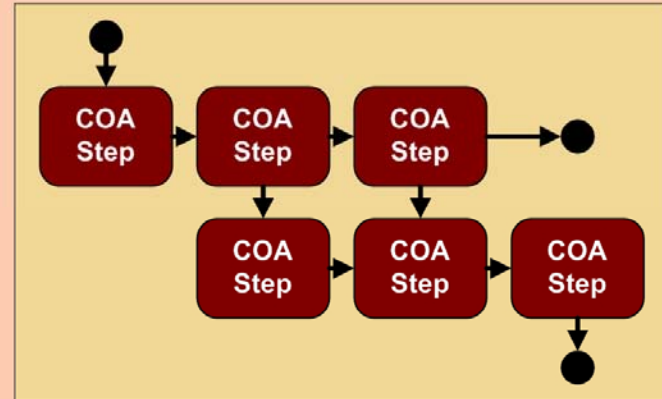
Basic Structure of FACET Models

FACET Course Of Action (COA) objects represent social behavior patterns

COA model: network of individual steps, represented by “Step” objects.

Steps are essentially **sub-models**.

Each Step is like a scene in a play, with cast of characters (agents), props (agents' resources), and locale.



Each Step:

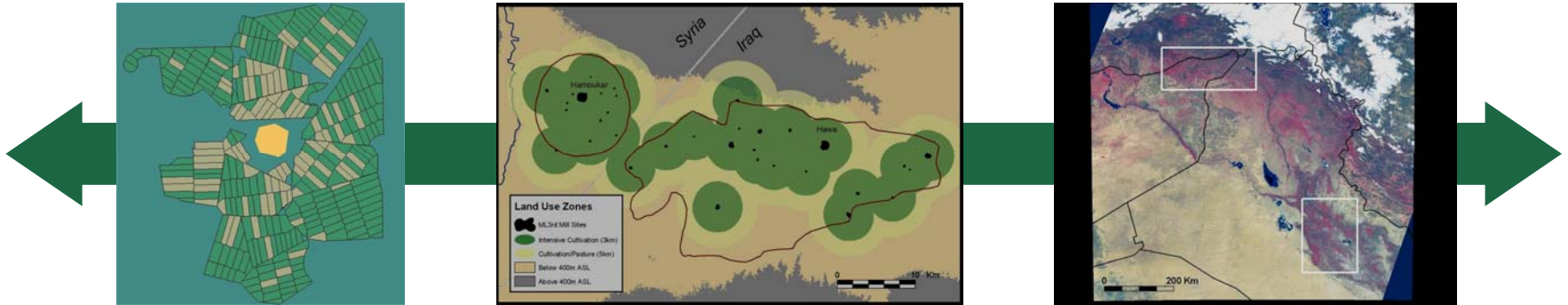
Requires resources held by agents participating in the action;

Consumes a specified interval of time, during which the agents and resources are committed to the step and thus unavailable for other activities;

Results in changes to the attribute values of some of the participants, and/or changes to attribute values of other domain objects that had been declared to be of interest to the COA.

Scope and Scale of Simulations

SCOPE: Individual small settlements up to whole regions (> 100 km)



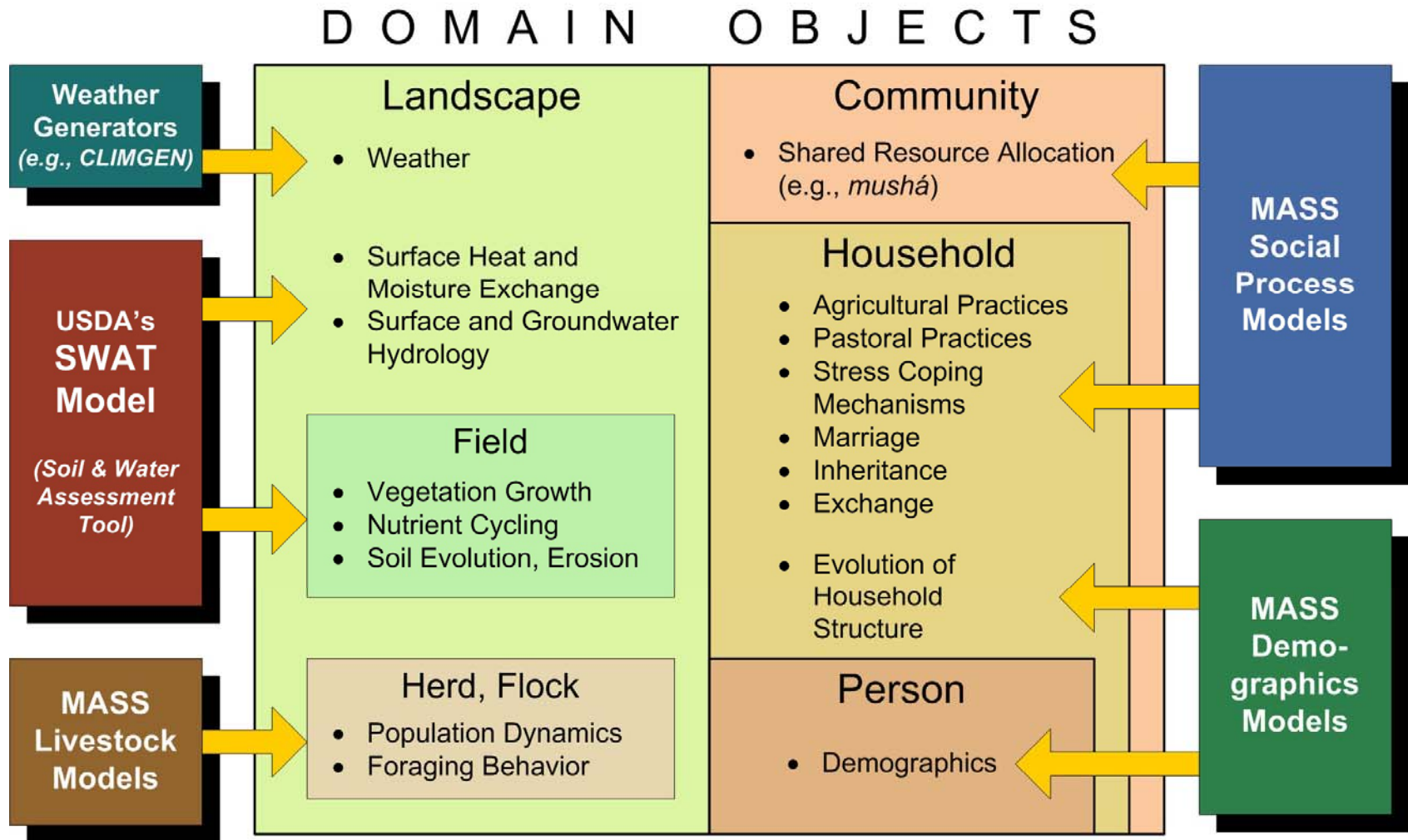
SCALE: *Entity-Level Resolution and Granularity*

- Individual households and persons as independent social agents
- Individual crop fields, domesticated fauna

SCALE: *Process and Temporal Resolution*

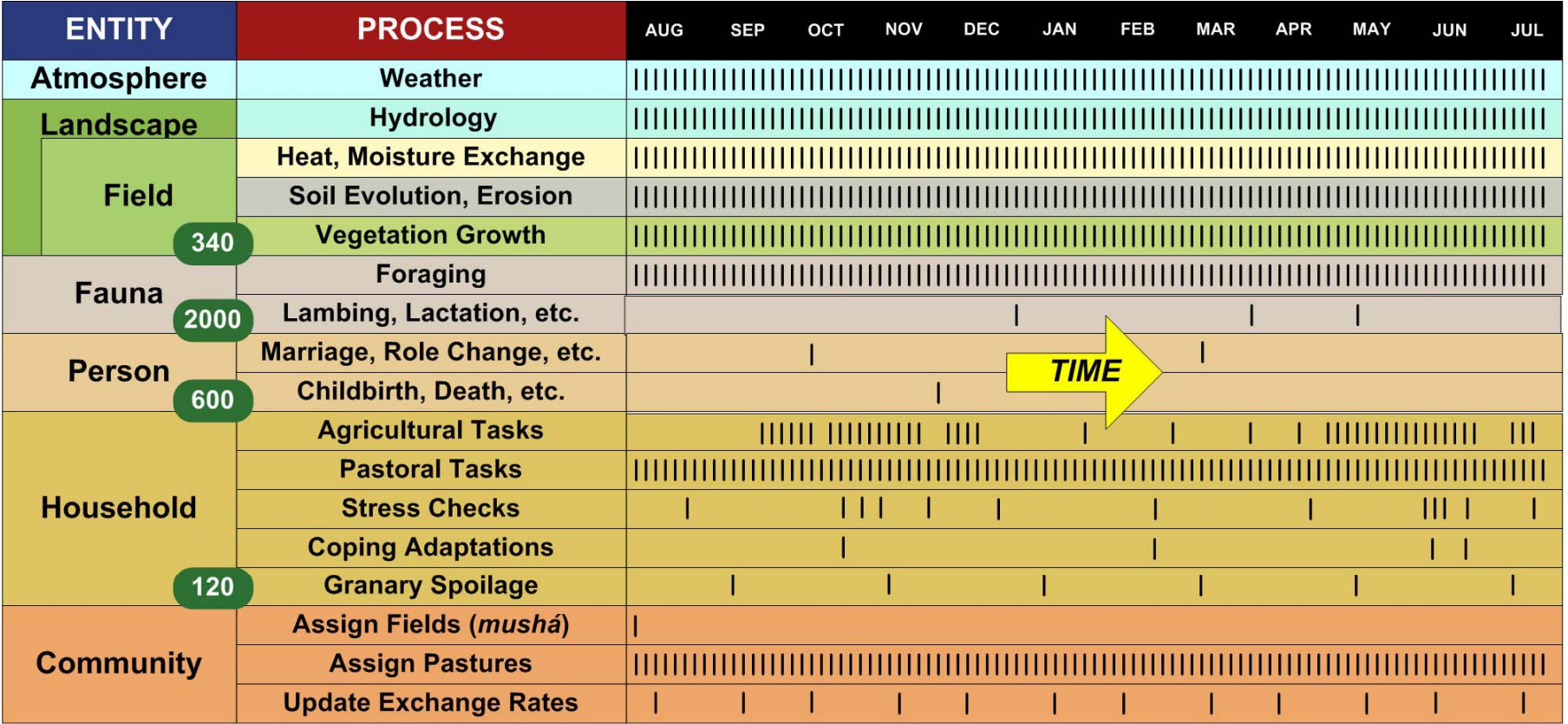
- Daily weather, hydrologic and soil processes, vegetation dynamics
- Daily to sub-daily (hours, minutes) tracking of detailed household tasks and social interactions

ENKIMDU Simulation Representation of Key Domain Objects and Their Dynamic Behaviors



(MASS: Modeling Ancient Settlement Systems Group)

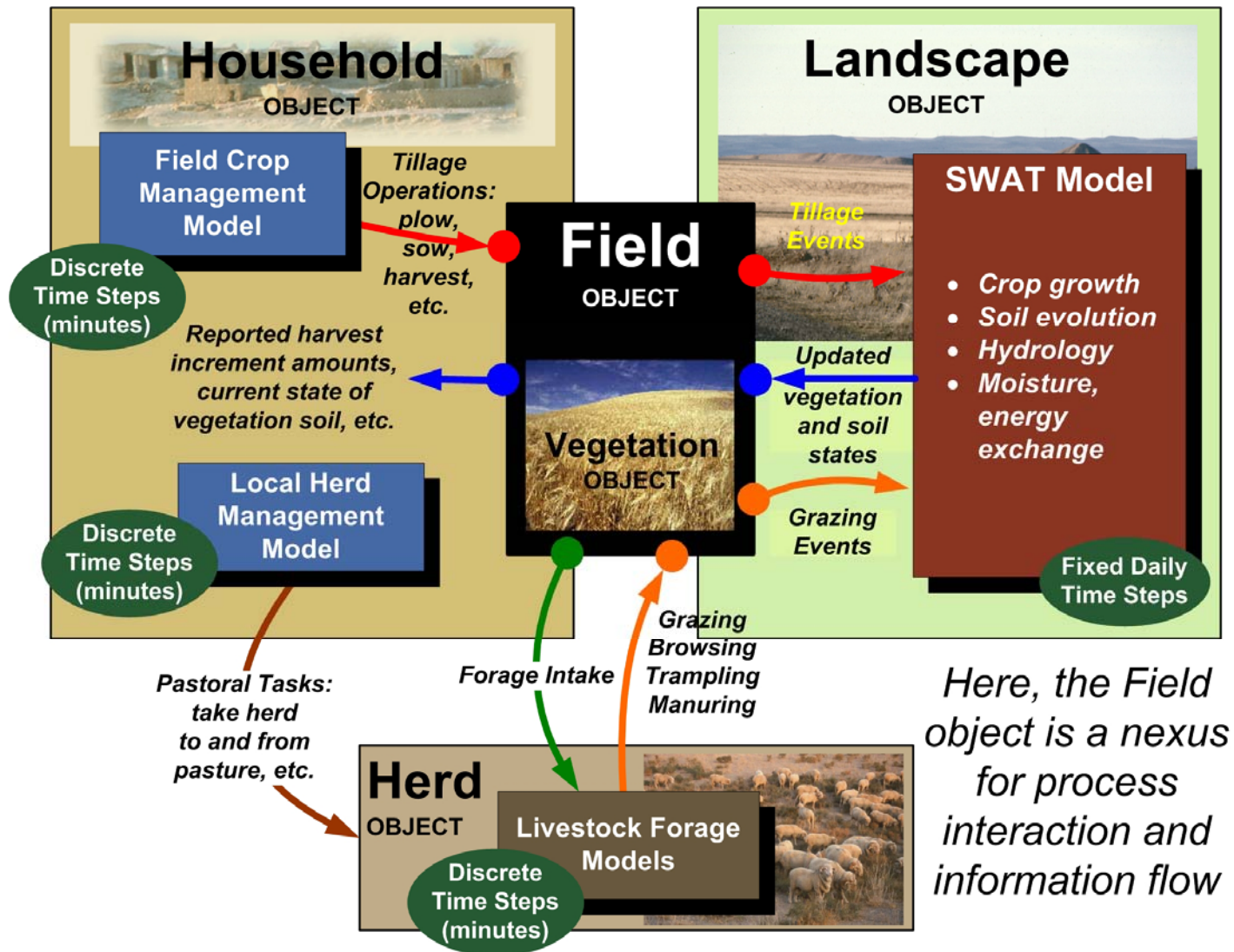
Temporal Texture of Modeled Concurrent Natural and Societal Processes



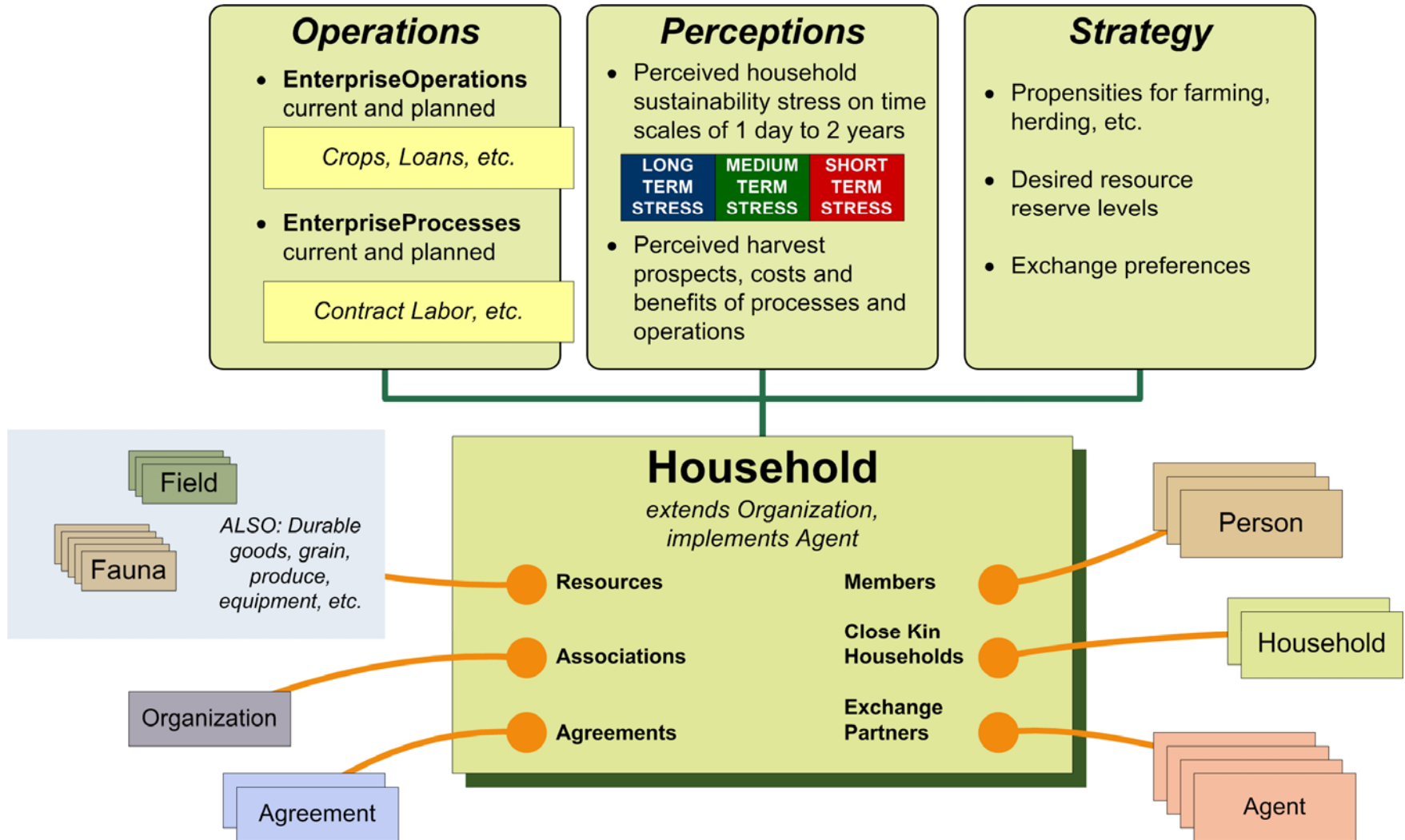
TICKMARKS INDICATE MODELED INVOCATION OF THE PROCESS BEHAVIOR

N *Approximate number of instances of this type in the Beydar settlement simulations*

Example of a Simulated Natural / Social Process Interaction



Composition of Household Agent Objects



Demographic and Kinship-Based Social Processes Simulated in ENKIMDU

- **Population generator:** *based on attested demographic models for ancient Mediterranean populations; Household characteristics from census data for Roman Egypt*
- **Modeled Processes:**
 - Birth rates
 - Death probabilities by age, gender
 - Household structure: five major types:
Multiple, Extended, Nuclear, Unrelated, Solitary
 - Age- and gender-dependent person role changes
 - Marriage
 - Inheritance
 - Household restructuring and evolution; fission and aggregation
 - Kin-gifts of food and labor

Subistence-Based Social Patterns: Household Agricultural and Pastoral Tasks

Agriculture

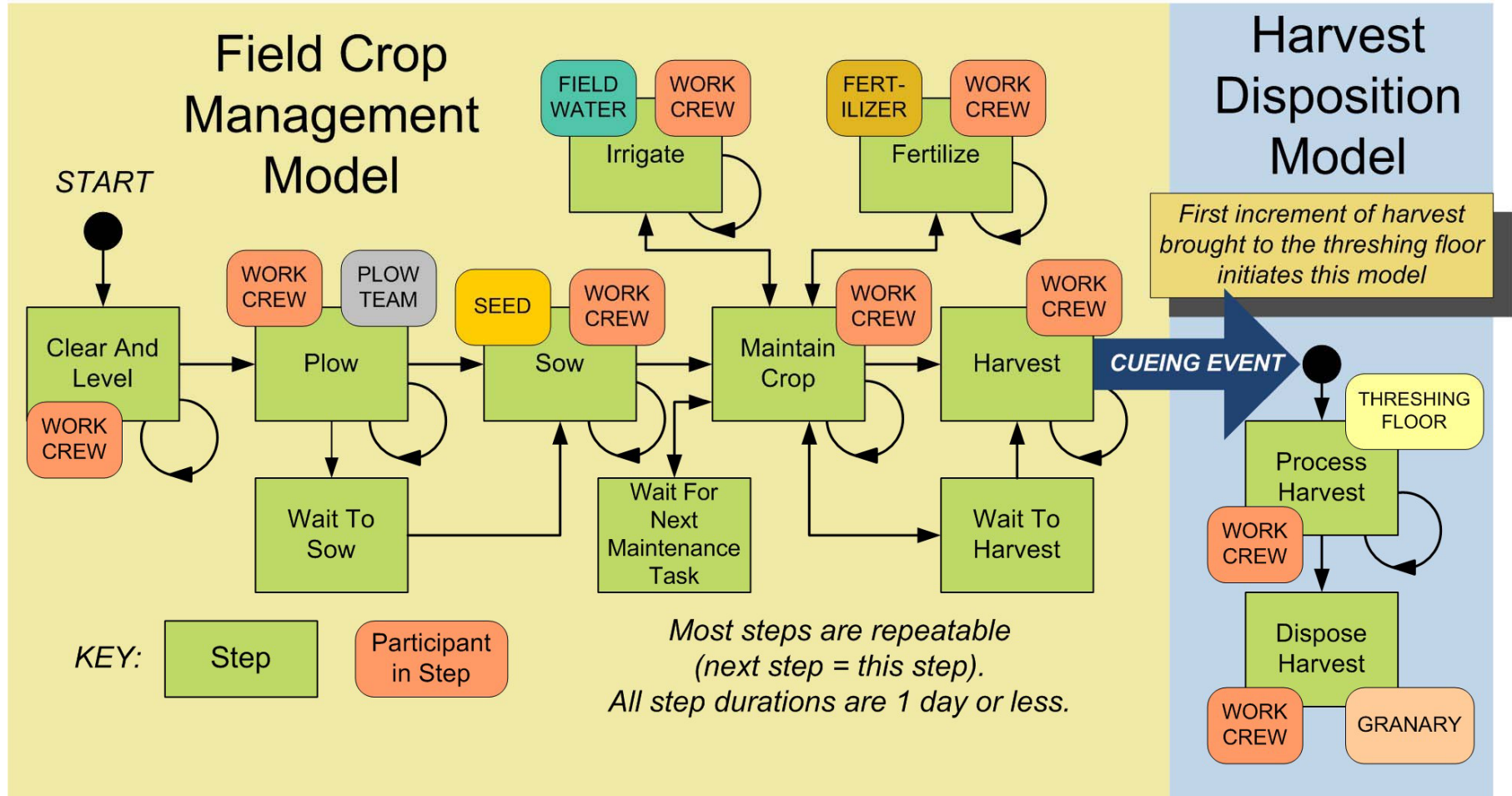
- Household crop fields owned or assigned by community lottery (*mushá*).
- Attempt to grow grain if possible; try to overproduce → safety margin.
- Households form task-specific work crews for crop tasks: clear and level the field, plow, sow, weed and maintain, harvest, and process harvest for storage.

Pastoralism

- Multi-household Herding Cooperative agents manage daily tasks: assemble herd, drive it to/from pasture, disperse it to its households. Herd sizes generally 100 to 300 animals.
- Livestock consumption: feasts, herd culling, and as a last-ditch coping measure. Dairy products also consumed daily.

Household Agents' Agricultural Social Pattern Models

Planting a barley crop: a household coping response to perceived future food stress

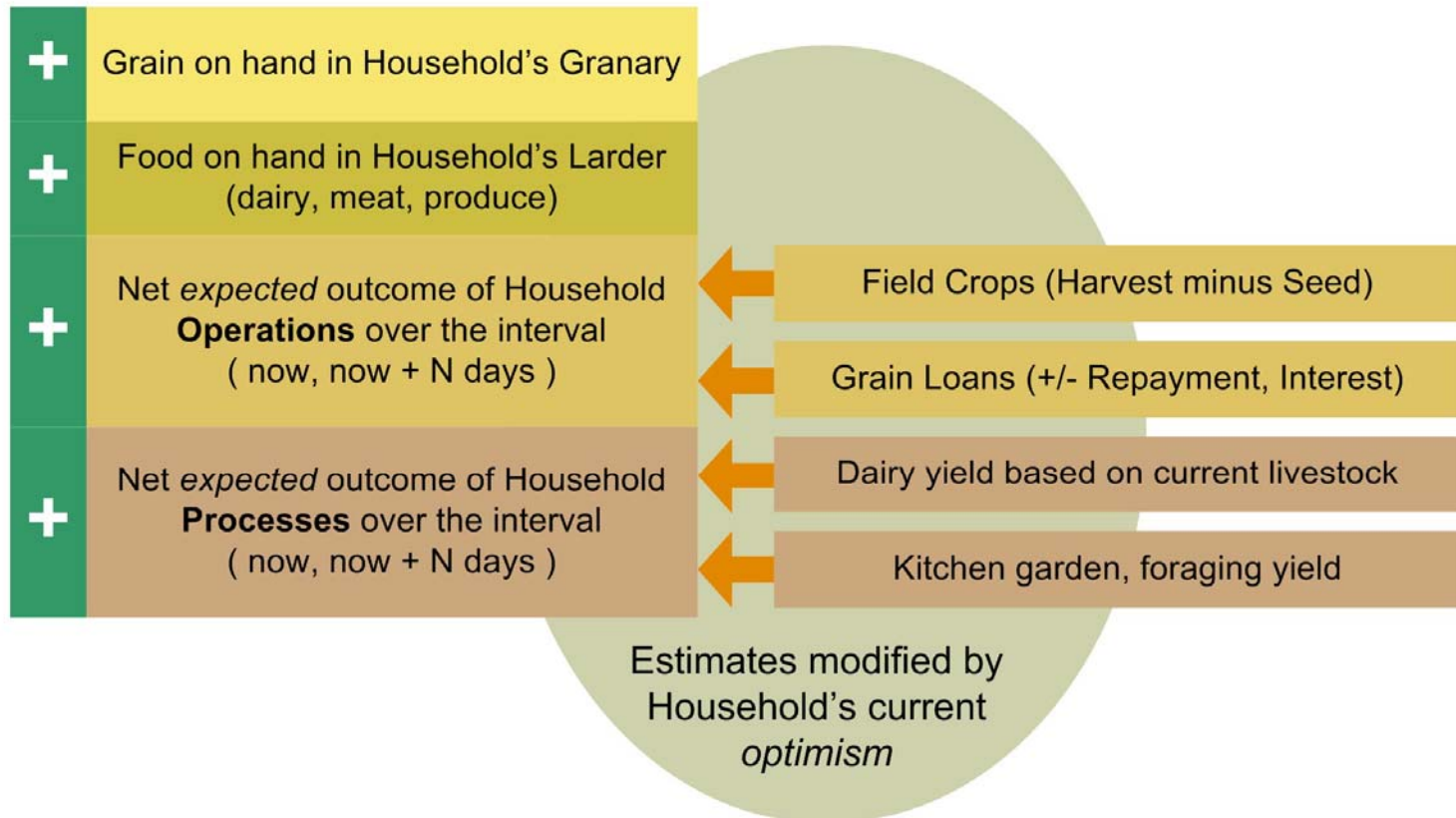


These two models are implemented using Argonne's FACET framework

Household Perceptions: Food Sufficiency

$$\text{Sufficiency(N days)} = \frac{\text{Expected Food Available (now to now + N days)}}{\text{Expected Food Consumption (now to now + N days)}}$$

Expected Food Available =



Household Perceptions: Food Stress

Define Stress(N days) =
 $1 - \text{Sufficiency(N days)}$
... but not < 0.

Household Stress Checks:

- Periodic, as function of stress levels
- After *any* change in household resources or structure

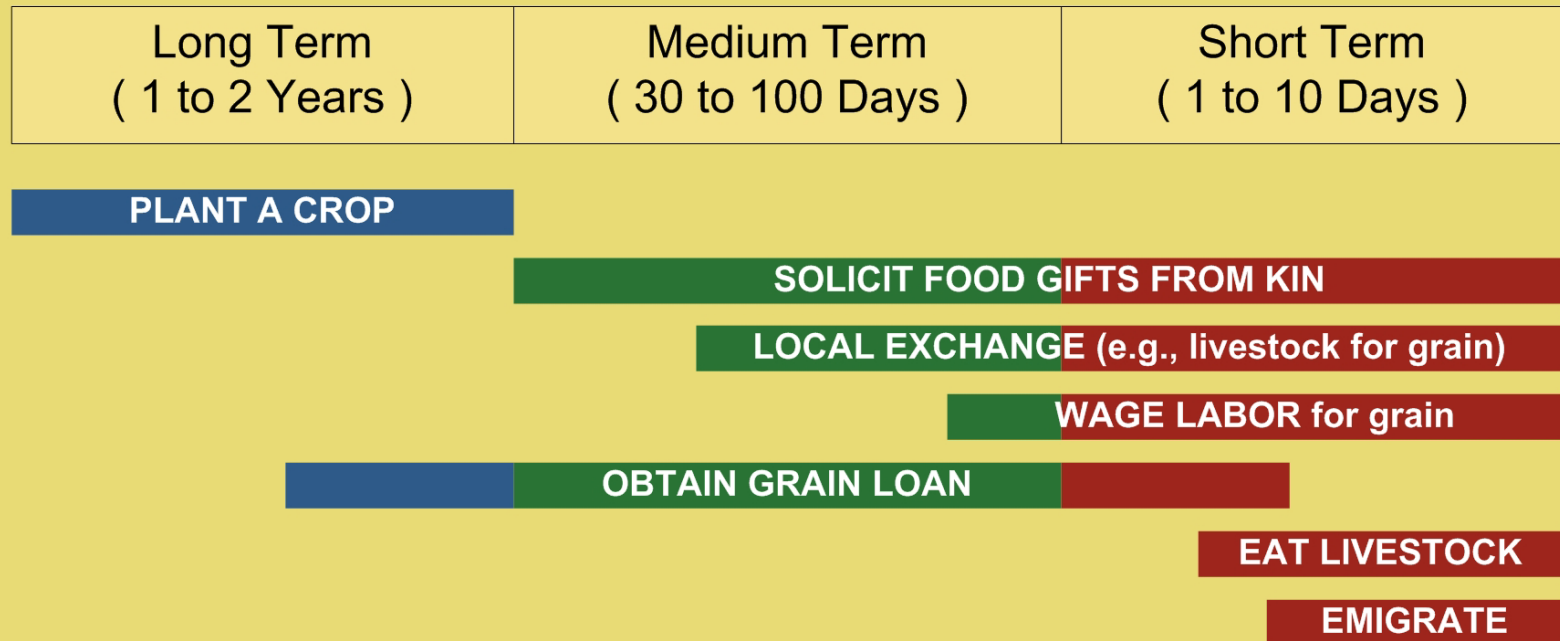
- **Short Term Food Stress** = $\text{Max}(\text{Stress}(\text{3 days}), \text{Stress}(\text{10 days}))$
- **Medium Term Food Stress** = $\text{Max}(\text{Stress}(\text{30 days}), \text{Stress}(\text{100 days}))$
- **Long Term Food Stress** = $\text{Stress}(L \text{ days})$
Where L = number of days till just before harvest after next ...
thus ~ 1 to 2 years ahead

A Household's repertoire of coping responses can be quite different for different stress time scales...

Household Agent Adaptive Behavior Examples

Household agents' perception of sustainability stress can drive them to initiate complex behavior patterns, as here ...

Modeled Household Food Stress Coping Mechanisms



Household preference order for coping responses is top-to-bottom

Exchange

Kin Gifts

- Household Agents can call on their close kin for non-reciprocal assistance.
- Preference order for requests: father, patrilineal uncles, brothers, patrilineal cousins, mother, matrilineal uncles, matrilineal cousins.

Reciprocal Exchange

- Household Agents prefer their established Exchange Partners but will exchange with any other cooperative agent.
- Both parties must perceive a significant benefit in exchanges.
- Exchange rates vary by time and by Market (e.g., Local and Ephemeral Markets).

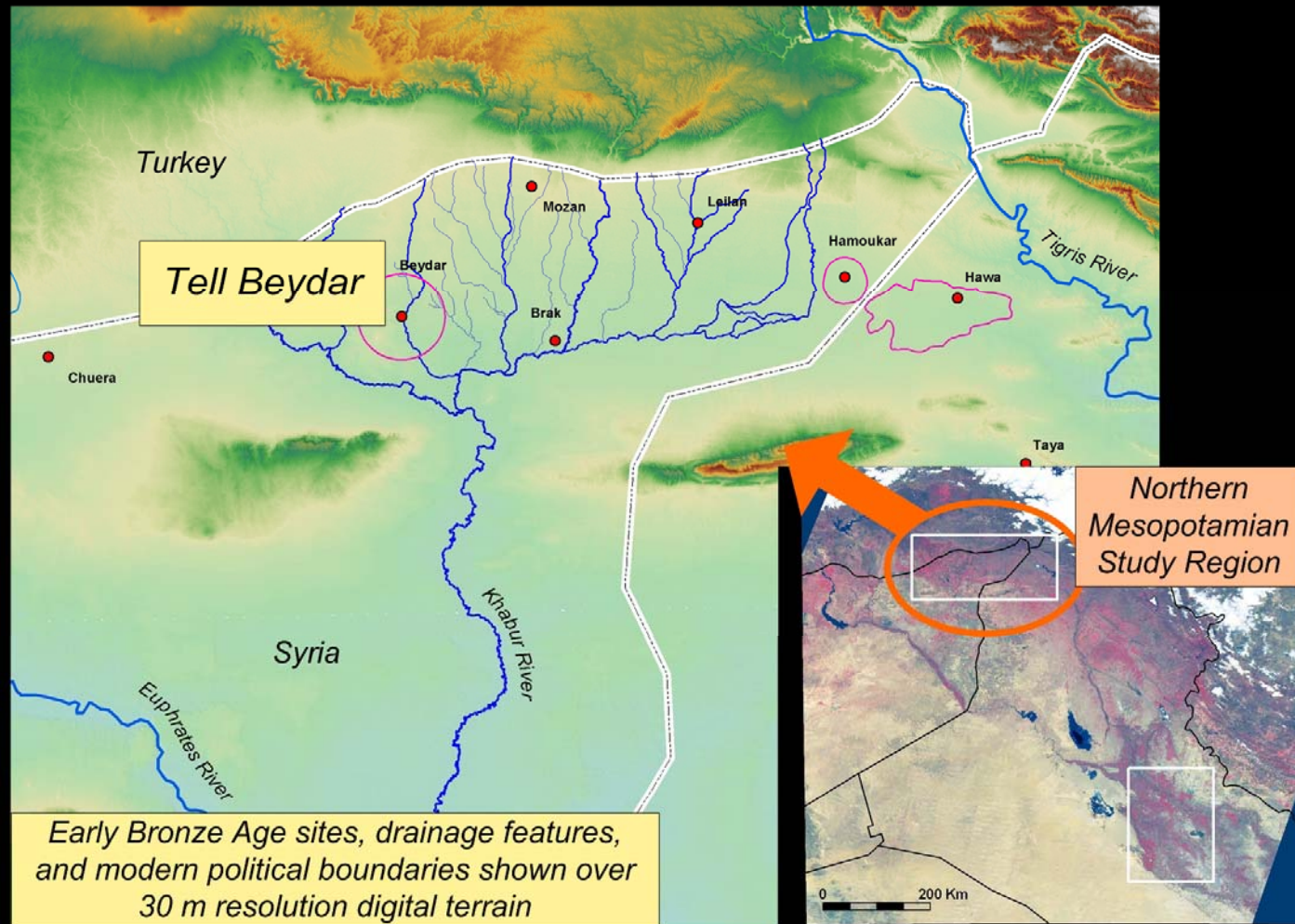
Wage Labor

- Exchange is reciprocal; day labor is paid each day in grain.

Grain Loans

- Loans due to be repaid in kind, with interest (~ one-third of principal) after next harvest.

Northern Mesopotamian Pilot Site: Tell Beydar



Computer Model of Bronze Age Tell Beydar

A reconstruction based on site surveys and regional analogs:

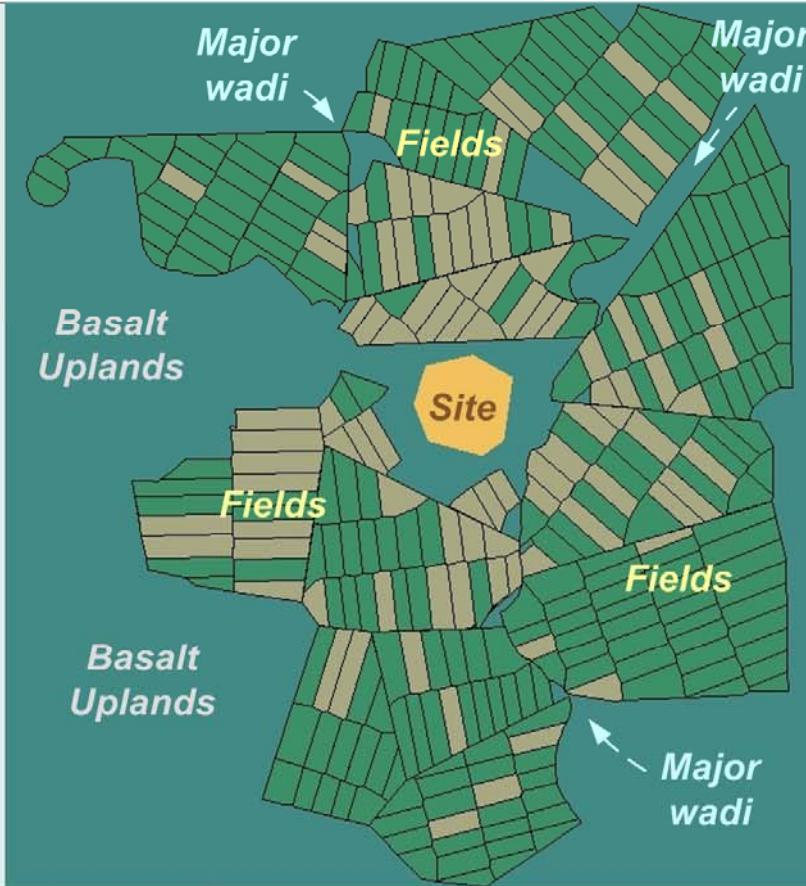
Tell Beydar Field Layout

Surrounding the Tell Beydar settlement site to a radius of roughly 2 km:

337 fields averaging about 3 ha each
→ 1,000 ha total

Fields excluded from basalt highlands to west and from courses of major wadis

Soils: calciorthid silty loam; alluvial in wadis; thinly covered basalt formations to west.



Other Key Data Sources And Assumptions

Weather: 100 years of daily weather synthesized from long-run Mosul, Iraq climatological data.

Crops: Barley only, with botanical parameters adjusted for archaic genotypes.

Livestock: Sheep and goats, with zoological parameters typical of Middle Eastern varieties.

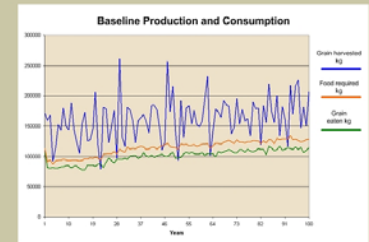
ENKIMDU's Currently Available Output Streams



Geospatial Animation Displays
Queryable, with zoom, pan, etc.;
fine temporal resolution down to one
simulation minute update interval



Settlement Annals
Nomadic Community Annals
Household Annals
*Summaries of activities by year,
month and/or n-day period,
in Excel spreadsheet format*



Ephemeral Market Summaries

*Summaries of exchanges by
day and/or for entire market
duration, in Excel
spreadsheet format*

*Ephemeral Market: e.g.,
exchanges between nomads
and townspeople during a
two-week visit to a town by a
nomadic group*

Household Diaries
*Year-by-year chronological
narrative description of all
significant activities of each
household and its members*

HOUSEHOLD NUMBER 1 DIARY FOR YEAR 14	
Head:	carl1(63) 4 Member(s):
Fa:	brad9(15) Mo: cynthia50(15)
Fa:	carl1(63) Mo: amanda2(52)
Close Kin:	Br:4
Exchange Partners:	130 138 21 88 110 45 123
Resources:	field shares: 2.0 stored grain: 567.8 kg
HOUST	
Head:	
Fa:	
Close Kin:	
Exchange Partners:	
Resources:	
1 goat:	
36 >	Provided 104.7 kg grain to H110 in exchange for a goat
7 >	Pro in
126 >	Provided 112.0 kg grain to H123 in exchange for a sheep
361 >	Grain gift of 52.0 kg given to sib (H170)
336 >	MARRIAGE: nina8(14) has married george452(16) /H66
336 >	nina8(14) , new wife of george452(16) /H66 moves out to join her husband
354 >	Grain gift of 6.8 kg given to p nephew (H114)
354 >	Grain gift of 40.4 kg given to p nephew(H114)

Key to Household Diary Results

Household structure and resources at beginning of simulation year (August 1, or Sim Day Number 0)

HOUSEHOLD NUMBER 1 DIARY FOR YEAR 6

Head: carl1(55) 5 Member(s):
Fa: carl1(55) **Mo:** amanda2(44) **Off:**(brad9(7) ted7(21) nina8(9))
Close Kin: Br:5 4
Resources: field shares: 3.0 stored grain: 2143.9 kg
 2 sheep

172 > MARRIAGE: ted7(21) has married delilah214(26) /H42

172 > delilah214(26) , new wife of ted7(21) moves in with her dependents: xena538(3) lou620(0) zack586(1)

172 > A family unit departs to form a new household:
Fa: ted7(21) **Mo:** delilah214(26) **Off:**(xena538(3) lou620(0) zack586(1))

Persons are identified uniquely by randomly assigned name plus integer identifier, with current age in parentheses – here, nina8 is 9 years old

“Embedded” **nuclear families** listed as Father, Mother, (Offspring list)

Close Kin: Household ID numbers of households headed by close kin of this household’s head (carl1).

“**Outsiders**” have /H(household ID Number) appended after their age – thus delilah214 had been a member of Household 42.

Significant events for year, prefaced by Day Number >

- Demographic Events
- Resource Allocation Events

HOUSEHOLD NUMBER 21 DIARY FOR YEAR 6

Head: john97(58) 6 Member(s):
Fa: john97(58) **Mo:** mary98(53) **Off:**(herman101(12) ursula103(9) bambi104(10))
 gigi100(67)
Exchange Partners: 2 100
Resources: field shares: 2.0 stored grain: 3055.3 kg
 3 sheep 2 goat(s)

17 > Grain gift of 35.6 kg given to son (H129)

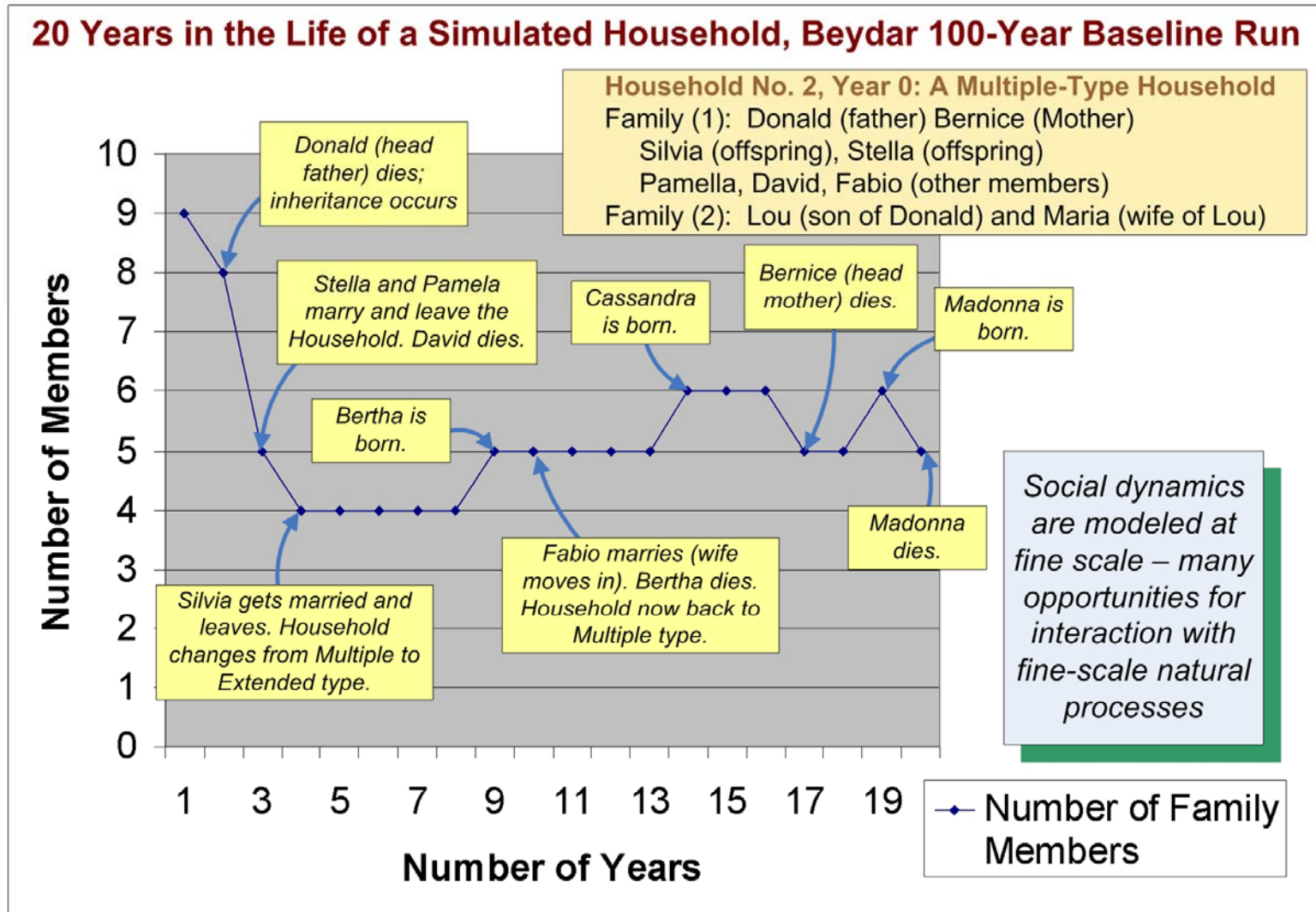
309 > Labor gift of 17.4 person-days given to son (H105)

“**Other**” members not part of nuclear families (gigi100 here) are listed last

Exchange Partners: ID numbers of households that have exchanged commodities with this household

Here, Household 21 has given **gifts** to Households 105 and 129, which are headed by sons of the household’s head, john97

Beydar Baseline Run: A Modeled Household's Time History Shows Turbulent Social Dynamics



Snapshots from Tell Beydar 100-Year Baseline Simulation: Households' Daily Agricultural and Pastoral Activities

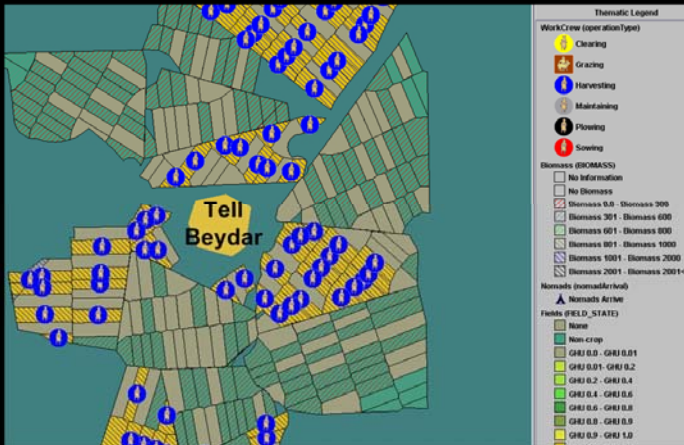
Autumn: Field Preparation, Plowing and Sowing



Winter / Early Spring: Weeding, Light Maintenance Tasks



Late Spring / Early Summer: Harvest



Late Summer: Fields Rest; Grazing Continues



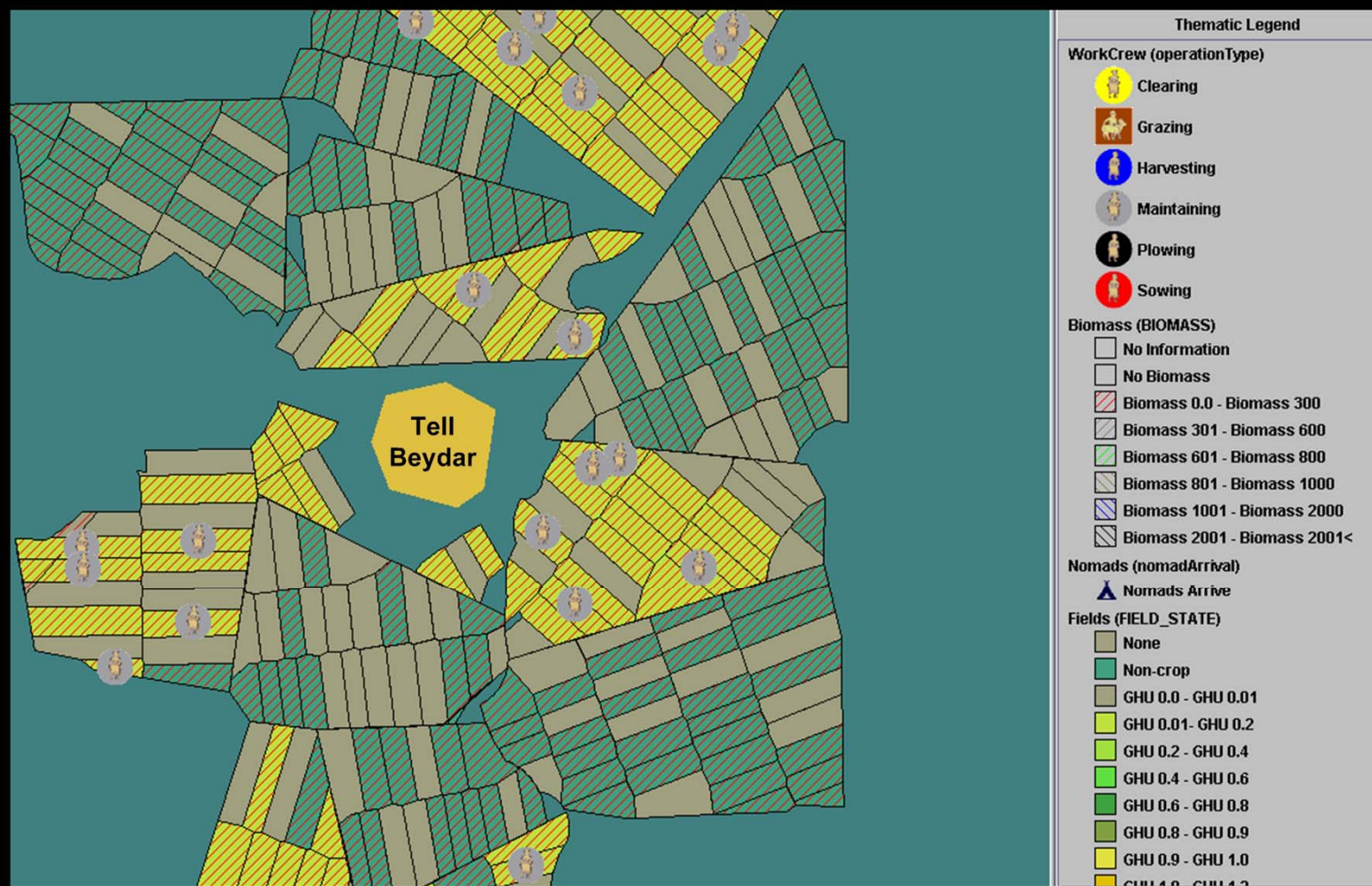
Households' Daily Agricultural and Pastoral Activities - I

Autumn: Field Preparation, Plowing and Sowing



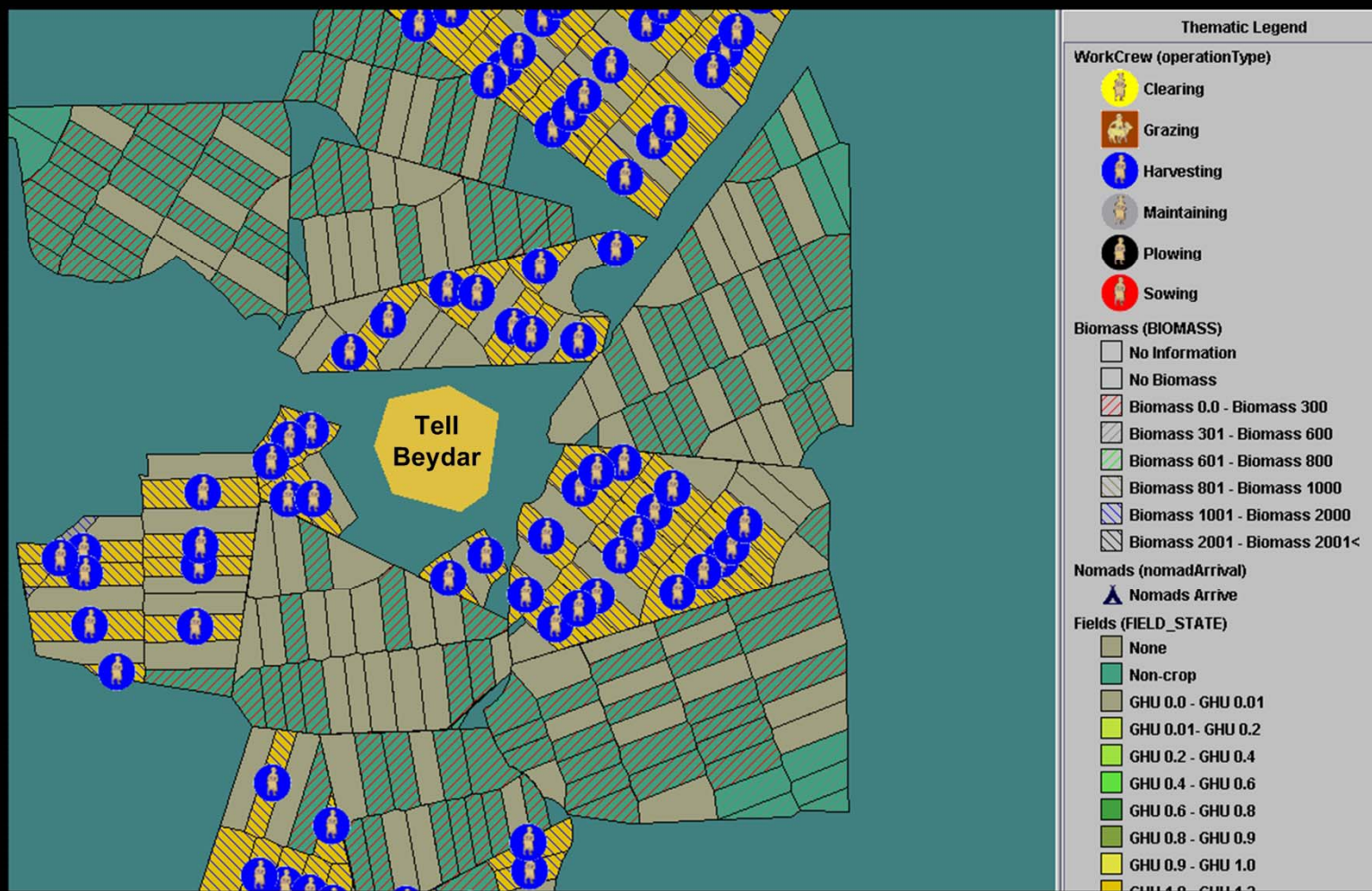
Households' Daily Agricultural and Pastoral Activities - II

Winter / Early Spring: Weeding, Light Maintenance Tasks



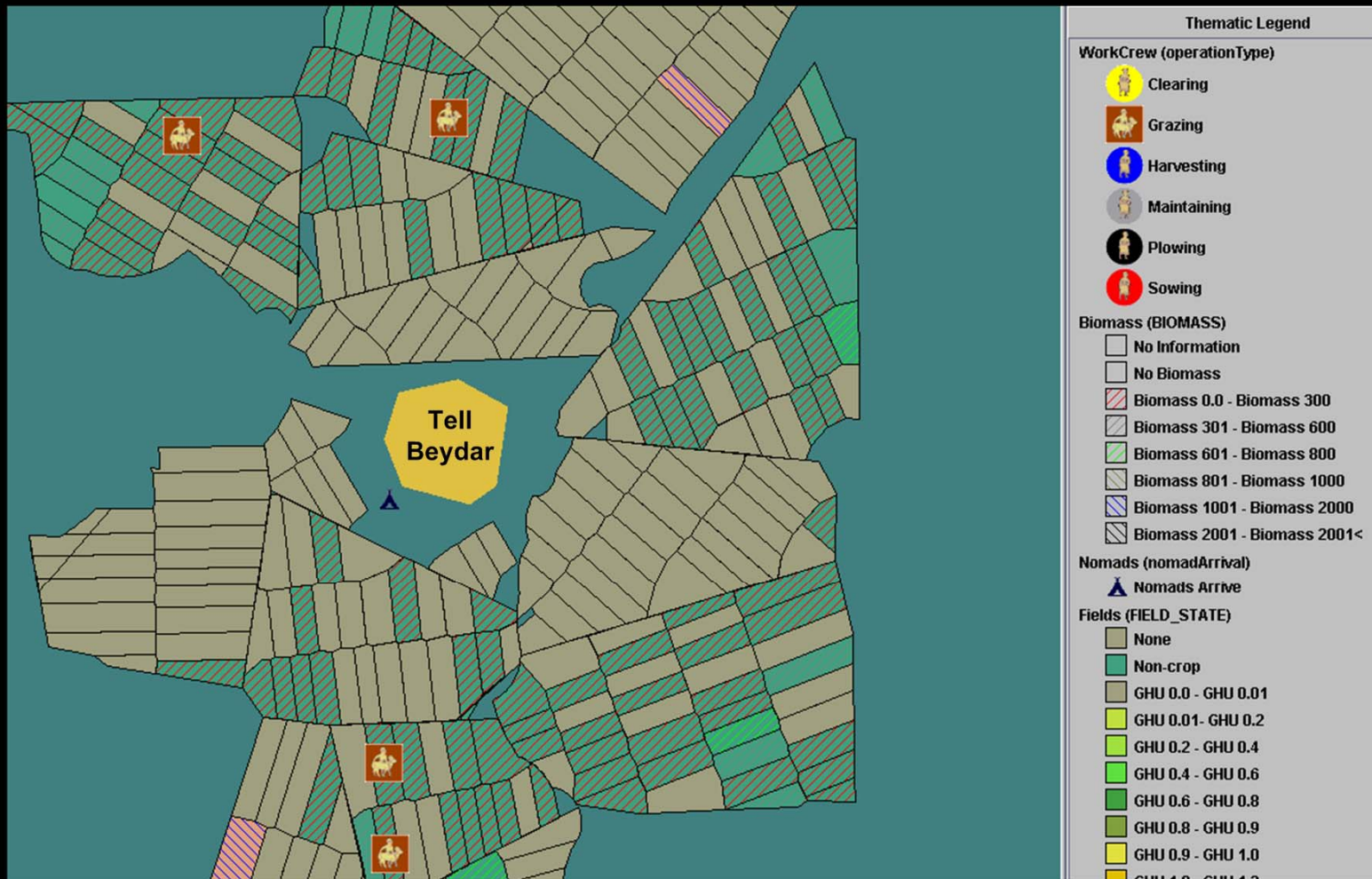
Households' Daily Agricultural and Pastoral Activities - III

Late Spring / Early Summer: Harvest



Households' Daily Agricultural and Pastoral Activities - IV

Late Summer: Fields Rest; Grazing Continues



Tell Beydar 100-Year Baseline Scenario

Initial Population: 501 persons in 99 households;
1,188 initial livestock, 12 per household.

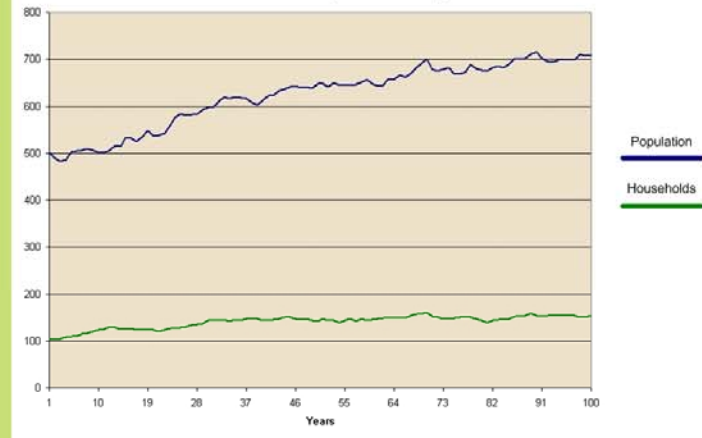
Fields allocated to households via *mushá* (community field lottery) system. Biennial following strictly observed by all households. Ard plow or hoe used for tillage.



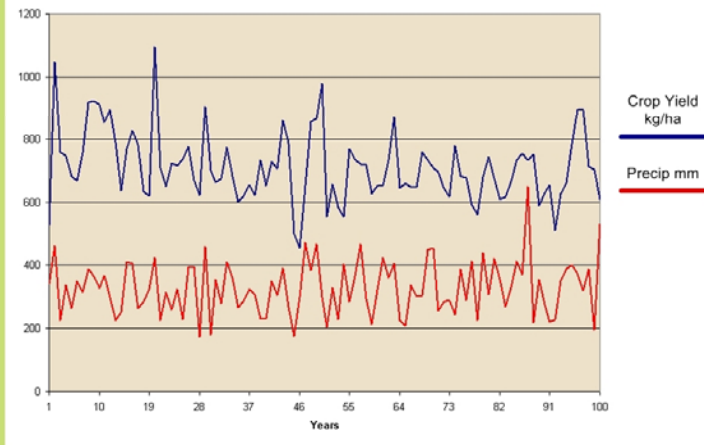
**"Garden of Eden"
assumption:**

*no exceptional environmental
or societal stresses are imposed.*

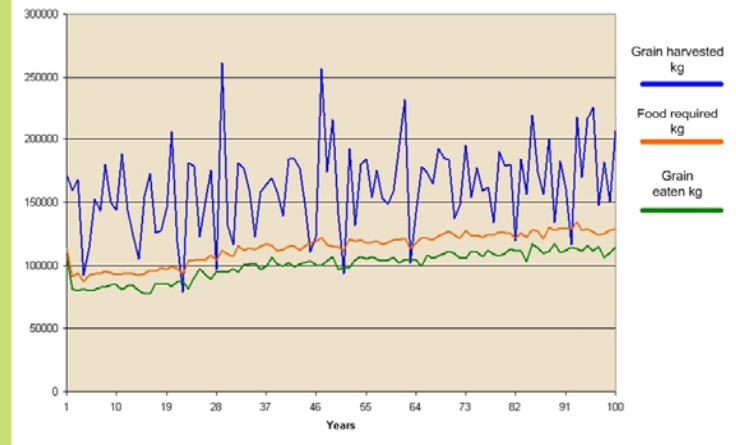
Baseline Population Dynamics



Baseline Barley Yield and Precipitation



Baseline Production and Consumption



Tell Beydar Scenario Variant Studies

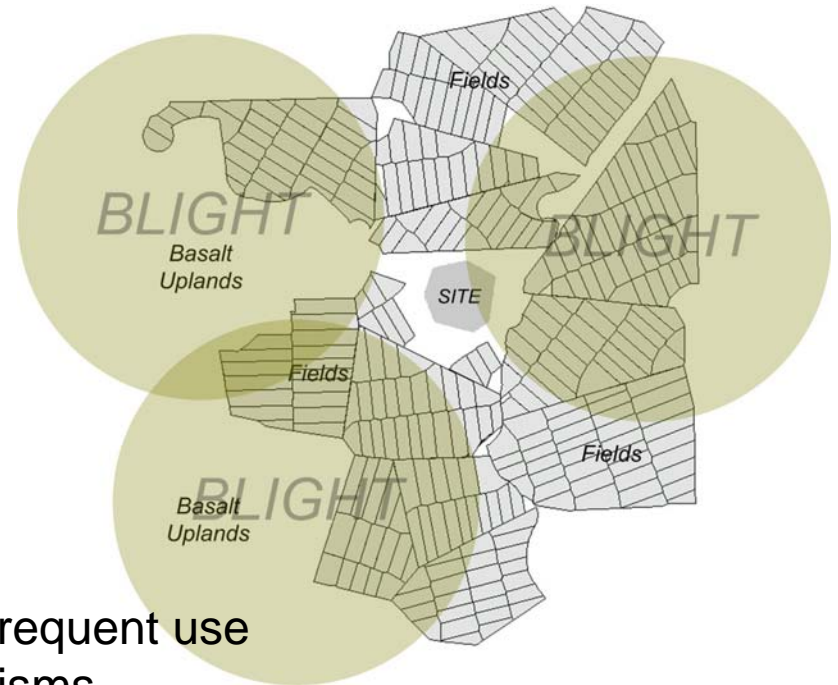
- **Chronically recurring harvest blight**
- **Acute five-year drought**
- **Chronic farm production bottleneck (plow team availability)**
- **Corvee episode (→ labor shortage at harvest)**
- **Diphtheria epidemic**

Scenario Variant: Harvest Blight

This scenario variant assumes the presence of a chronically recurring harvest blight:

- Random patches of 1 km radius
- Harvest loss 80 – 90 pct. within patches
- Annual probability of blight ~ 50%
- Areal coverage of patches ~ 50%

→ space/time average crop loss ~ 20%



Chronic stress drove households to more frequent use of exchange-based coping mechanisms

	Livestock Sold Per Year Per Household	Grain Gifts Per Year Per Household	Grain Loans Per Year Per Household
Baseline Case Mean	0.0966	0.0599	0.3488
Blight Case Mean	0.1542	0.0845	0.4602
Blight / Baseline	1.60	1.41	1.32

Blight case population curve is flat: 2% drop over 100 years

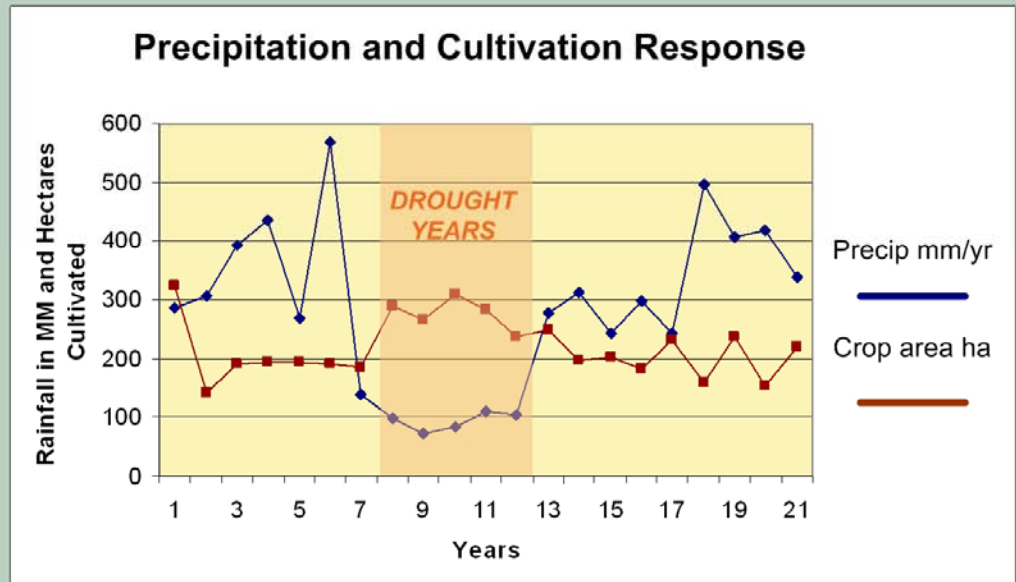
Scenario Variant: Severe Drought

In this scenario, a severe drought (precipitation ~ 100 mm/yr) was imposed for simulation years 8 through 12.

Lower yields during drought prompted households to extensify: increase area planted in grain to offset per-hectare yield shortfalls.

Households also temporarily increased volume of transactions: kin gifts, livestock sales, and grain loans.

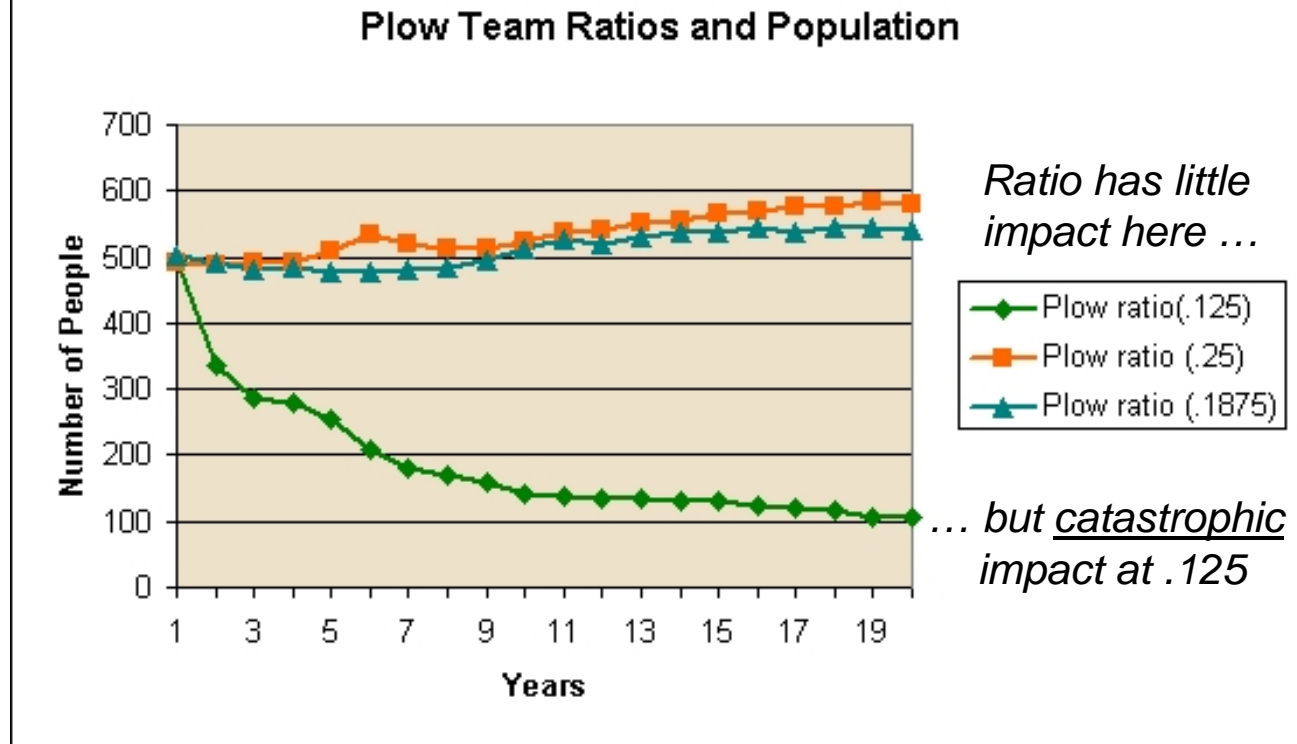
The model settlement was ultimately resilient; population was stable during the drought, and resumed slow rise thereafter. Biennial fallowing and availability of additional farm land likely helped to mitigate the crisis.



Scenario Variant: Plow Team Bottlenecks

This variant tests the sensitivity of the settlement to availability of a critical resource: plow teams.

For baseline run, plow team / household ratio was 0.5.



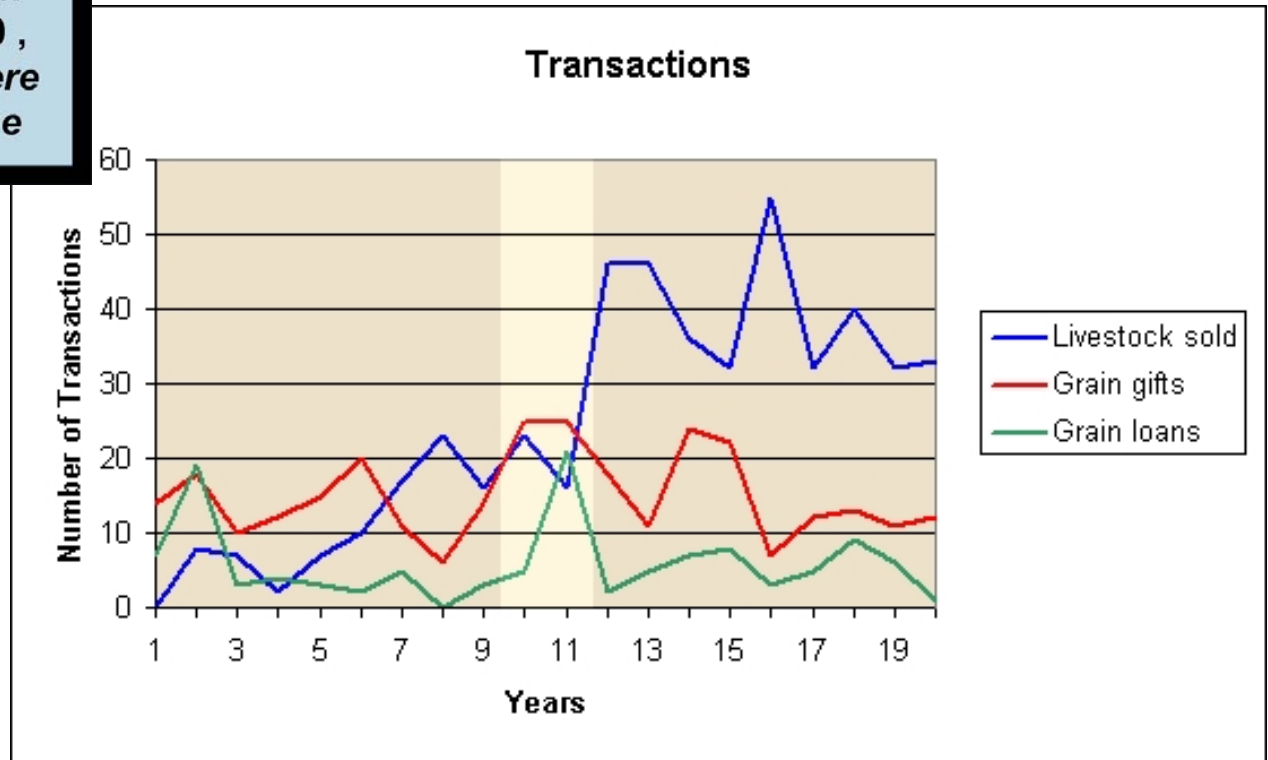
Note the strong aggregate system response as a “hidden” resource constraint is reached

Scenario Variant: Corvee Episode

For this variant, 90% of the adult males were removed from the settlement, from March through August of Year 10, and then returned – *but were unavailable at harvest time*

Much of the Year 10 harvest was left in the field.

Short-term adaptive response: increases in grain transactions, liquidation of herds



How did individual households cope with this dilemma?

“ Two households, both alike in dignity ... ”

From ENKIMDU Household Diary Output:

William Shakespeare,
Romeo and Juliet, Act I, Scene 1

HOUSEHOLD NUMBER 1 DIARY FOR YEAR 2

Head: carl1(51) 9 Member(s):

Fa: carl1(51) Mo: amanda2(40)

Off:(brad9(3) ted7(17) nina8(5))

Fa: samson3(24) Mo: bernice4(21)

isabella6(27) rocko5(39)

Close Kin: Mo:26 Br:5 4

Resources: field shares: 5.0 stored grain: 1744.1 kg
9 sheep 4 goat(s)

98 > MARRIAGE: rocko5(39)

has married delilah438(22) /H87

98 > delilah438(22), new wife of rocko5(39) moves in

111 > A family unit departs to form a new

household: Fa: samson3(24) Mo: bernice4(21)

111 > A family unit departs to form a new

household: Fa: rocko5(39) Mo: delilah438(22)

238 > MARRIAGE: isabella6(27)

has married rocko158(22) /H33

238 > isabella6(27) , new wife of rocko158(22) /H33
moves out to join her husband

240 > Grain gift of 47.9 kg given to son (H110)

HOUSEHOLD NUMBER 21 DIARY FOR YEAR 2

Head: john97(54) 10 Member(s):

Fa: fabio99(23) Mo: barbela107(24)

Fa: jerome102(16) Mo: nancy397(17)

Fa: john97(54) Mo: mary98(49)

Off:(herman101(8) ursula103(5) bambi104(6))
gigi100(63)

Resources: field shares: 4.0 stored grain: 2475.8 kg
5 sheep 3 goat(s)

0 > A family unit departs to form a new household:

Fa: fabio99(23) Mo: barbela107(24)

161 > Grain gift of 136.7 kg given to son (H109)

246 > Grain gift of 136.7 kg given to son (H109)

328 > Grain gift of 18.5 kg given to son (H33)

328 > Grain gift of 121.2 kg given to son (H33)

Year 10: The Year of the Corvee Episode

HOUSEHOLD NUMBER 1 DIARY FOR YEAR 10

Head: carl1(59) 4 Member(s):

Fa: carl1(59) Mo: amanda2(48)

Off:(brad9(11) nina8(13))

Close Kin: Br:5 4

Exchange Partners: 130 138 21

Resources: field shares: 2.0 stored grain: 3135.1 kg
1 goat(s)

7 > Provided 113.4 kg grain to H21
in exchange for a goat

several livestock transactions omitted

336 > MARRIAGE: nina8(14)
has married george452(16) /H66

336 > nina8(14) , new wife of george452(16) /H66
moves out to join her husband

354 > Grain gift of 6.8 kg given to p nephew (H114)

354 > Grain gift of 40.4 kg given to p nephew(H114)

**Household 1 has a stronger reserve
heading into a crisis year ...**

HOUSEHOLD NUMBER 21 DIARY FOR YEAR 10

Head: john97(62) 4 Member(s):

Fa: john97(62) Off:(herman101(16) ursula103(13))
gigi100(71)

Exchange Partners: 2 100 88 1

Resources: field shares: 2.0 stored grain: 1363.1 kg
2 goat(s)

7 > Provided a goat to H1
in exchange for 113.4 kg grain

26 > Grain gift of 42.4 kg given to son (H129)

37 > DEATH: gigi100(71)

37 > Provided 123.5 kg grain to H1
in exchange for a goat

37 > MARRIAGE: ursula103(14)
has married george15(19) /H2

37 > ursula103(14) , new wife of george15(19) /H2
moves out to join her husband

57 > Provided a goat to H1
in exchange for 123.5 kg grain

57 > Provided a goat to H1
in exchange for 123.5 kg grain

122 > MARRIAGE: herman101(17)
has married tara464(14) /H116

122 > tara464(14) , new wife of herman101(17)
moves in

Year 11: In the Wake of the Corvee Episode

HOUSEHOLD NUMBER 1 DIARY FOR YEAR 11

Head: carl1(60) 3 Member(s):

Fa: carl1(60) Mo: amanda2(49) Off:(brad9(12))

Close Kin: Br:4

Exchange Partners: 130 138 21 88

Resources: field shares: 2.0 stored grain: 1314.5 kg
2 goat(s)

6 > Provided a goat to H138
in exchange for 109.8 kg grain

79 > Provided 77.7 kg grain to H88
in exchange for a goat

96 > Provided a goat to H138
in exchange for 77.7 kg grain

303 > Grain gift of 65.7 kg given to son (H110)

Household 1 shares its largesse ...

... while Household 21 struggles

HOUSEHOLD NUMBER 21 DIARY FOR YEAR 11

Head: john97(63) 3 Member(s):

Fa: herman101(17) Mo: tara464(14)
john97(63)

Exchange Partners: 2 100 88 1

Resources: field shares: 2.0 **stored grain: 56.7 kg**

64 > Obtained **grain loan** of 47.9 kg from H137

79 > Obtained **grain loan** of 46.0 kg from H123

79 > Obtained **grain loan** of 1.9 kg from H22

334 > Repaid 63.9 kg of grain loan in full to H137

334 > Provided 52.7 kg grain to H2
in exchange for a goat

several livestock transactions omitted

334 > Repaid 61.3 kg of grain loan in full to H123

334 > Repaid 2.6 kg of grain loan in full to H22

354 > Provided a goat to H152
in exchange for 62.2 kg grain

364 > Provided a goat to H130
in exchange for 62.2 kg grain

Year 14: Aftermath

HOUSEHOLD NUMBER 1 DIARY FOR YEAR 14

Head: carl1(63) 4 Member(s):

Fa: brad9(15) Mo: cynthia50(15)

Fa: carl1(63) Mo: amanda2(52)

Close Kin: Br:4

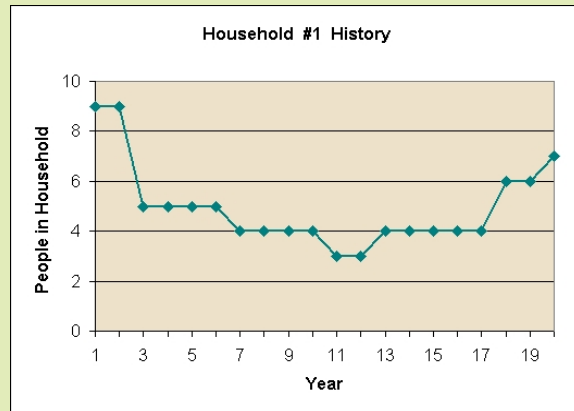
Exchange Partners: 130 138 21 88 110 45 123

Resources: field shares: 2.0 stored grain: 567.8 kg

36 > Provided 104.7 kg grain to H110
in exchange for a goat

126 > Provided 112.0 kg grain to H123
in exchange for a sheep

361 > Grain gift of 52.0 kg given to sib (H170)



HOUSEHOLD NUMBER 21 DIARY FOR YEAR 14

Head: john97(66) 4 Member(s):

Fa: herman101(20) Mo: tara464(17)

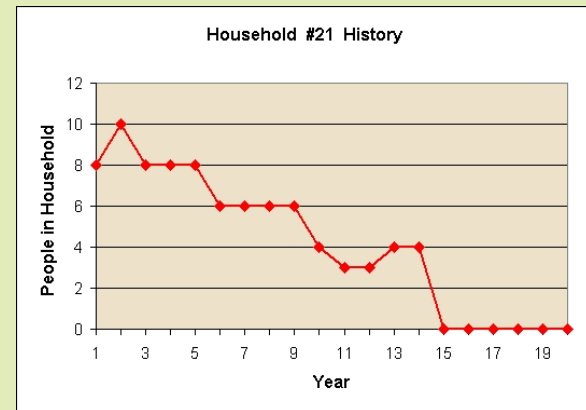
Off:(lisa798(1))

john97(66)

Exchange Partners: 2 100 88 1 137 123 22 152 130
151 110

Resources: field shares: 2.0 stored grain: 202.9 kg

322 > HOUSEHOLD DISSOLVED

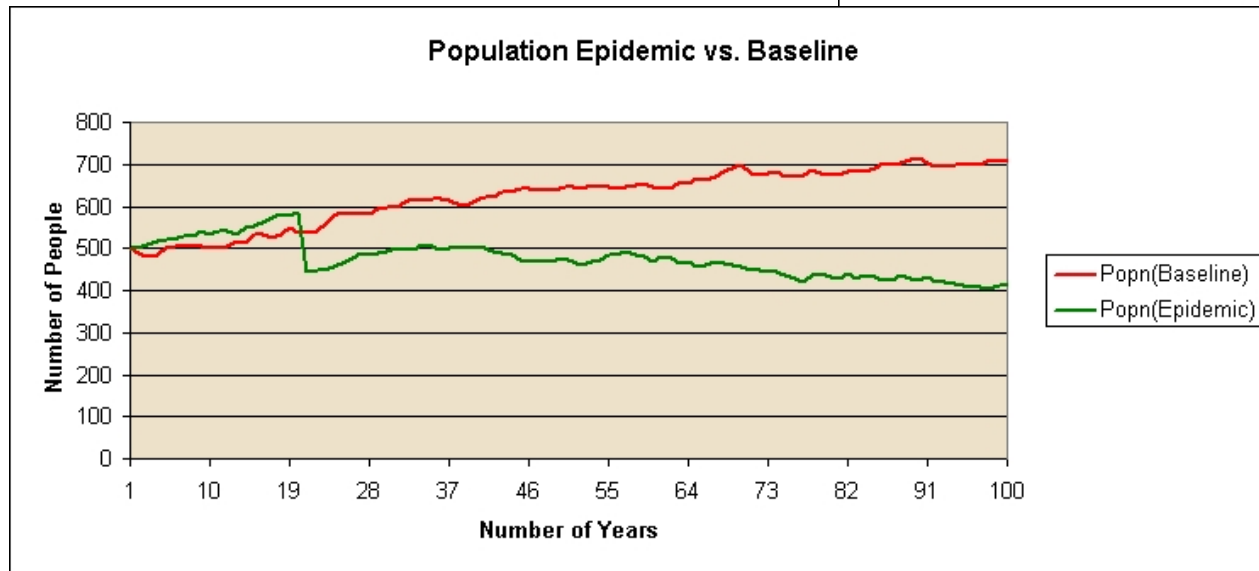
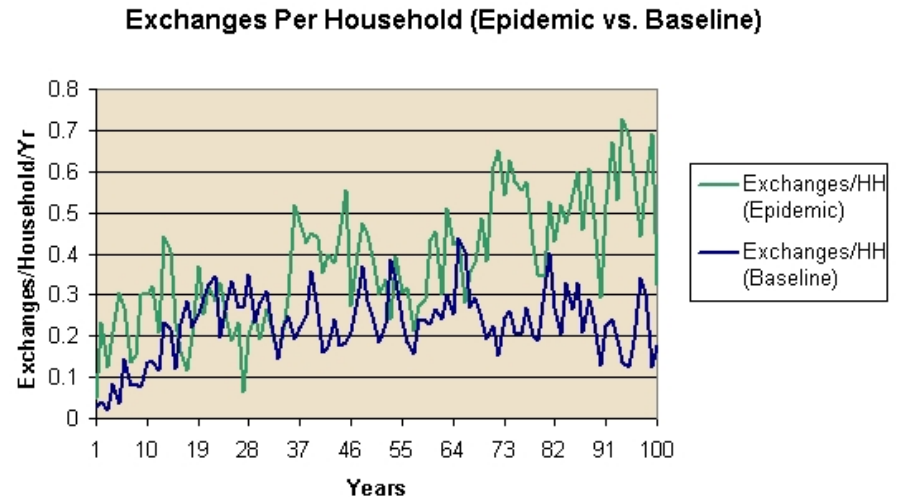


*... Household-level details, more than
aggregate community-level properties,
decided household sustainability*

Scenario Variant: Diphtheria Epidemic

A simulated diphtheria epidemic struck in Year 20 of this variant, killing 80 percent of the children and infants in the settlement.

Stress drove households to more and more exchanges:



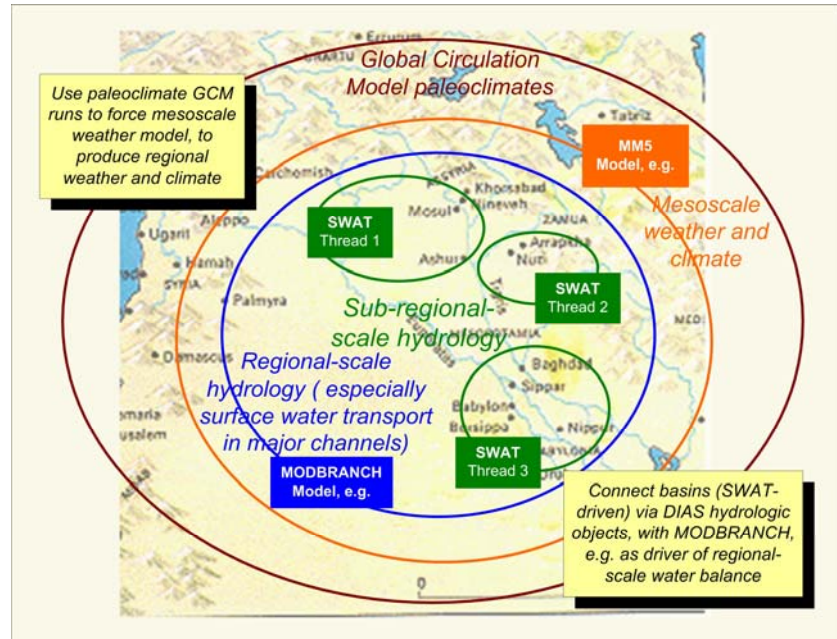
Settlement population growth failed to recover, even after three generations

Summary of Stress Scenarios

Scenario Name	Type of Stress	Description of Stress Scenario	Response of Simulated Settlement
Blight	Chronic Environmental Stress	<i>Recurring harvest blight, variable in space and time</i>	<i>Different households affected differently; increased use of exchange-based coping mechanisms</i>
Drought	Acute Environmental Stress	<i>Severe 5-year drought</i>	<i>Temporary extensification of agriculture to offset reduced yields</i>
Plow Team Shortage	Chronic Societal Stress	<i>Farm production bottleneck: plow team availability</i>	Abrupt collapse of settlement as “hidden” critical resource threshold is reached
Corvee Labor	Acute Societal Stress	<i>External call for corvee labor: unanticipated labor shortage at harvest time</i>	<i>Increase in grain transactions; liquidation of herds; effects felt for many years after corvee episode</i>
Diphtheria Epidemic	Acute Demographic Shock	<i>Diphtheria epidemic: sudden decimation of settlement’s children</i>	<i>Weakening of kinship networks; more non-kin exchanges; delayed shortage of farm labor; slow decline</i>

Major Ongoing Project Tasks

- Expand studies to sub-region and region scale in Northern Mesopotamia
- Implement and test Southern Mesopotamian pilot settlement model



- Strengthen the current agent representation – e.g.:
 - stronger person-level (vs. household-level) agency;
 - agent motivations beyond subsistence;
 - emergence and perpetuation of elites
- *New U. of Chicago / Argonne pilot study: modern Thai agro-economics*

Some Observations

BUILD MODEL → TEST & RUN MODEL → INTERPRET RESULTS ...

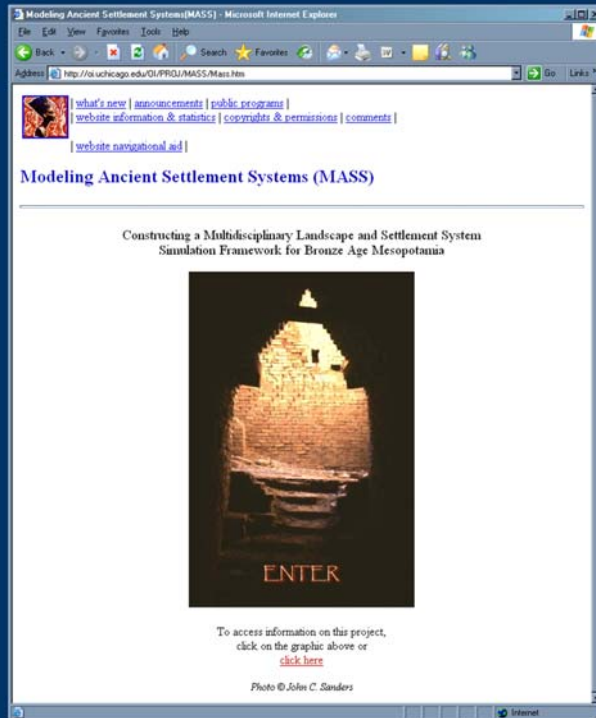
The most scientifically valuable part of this process may turn out to be the model-building phase!

As we attempt to include more and more complex real-world structures and mechanisms within our holistic simulations, we are uncovering more and more **knowledge gaps** -- technical issues that the scientific community has never before *needed* to resolve, and may never even have *identified* before. Discovering these is a good thing!

It appears that there could be *hundreds* of worthwhile dissertation topics waiting to be discovered in the process of constructing a modeling framework such as ENKIMDU. (*We've found dozens already*)

... And, Finally:

**PLEASE VISIT
OUR PROJECT
WEBSITE!**



**[http://oi.uchicago.edu/
OI/PROJ/MASS/Mass.htm](http://oi.uchicago.edu/OI/PROJ/MASS/Mass.htm)**

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